CURRENT STATUS OF THE DETECTOR DEVELOPMENT FOR THE FAR-INFRARED SURVEYOR (FIS) ON ASTRO-F

Shuji Matsuura, Midori Akazaki, Yosuke Isozaki, Hidehiro Kaneda, Takao Nakagawa, Mikhail Patrashin, and Mai Shirahata
The Institute of Space and Astronautical Sciences, 3-1-1 Yoshinodai, Sagamihara, Kanagawa 229-8510, Japan

Mikio Fujiwara
Communications Research Laboratory, 4-2-1, Nukui-kita, Koganei, Tokyo 184-8795, Japan

Yasuo Doi
University of Tokyo, Tokyo 153-8902, Japan

Yasunori Hibi, Takanori Hirao, Mitsunobu Kawada, Hirohisa Nagata, Hiroshi Shibai, and Toyoki Watabe
Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8602, Japan

Manabu Noda
Nagoya City Science Museum, 2-17-1, Sakae, Naka-ku, Nagoya 460-0008, Japan

ABSTRACT

ASTRO-F is a Japanese infrared satellite, which is scheduled for launch in early 2004. Far-infrared instrument that will be onboard the ASTRO-F, Far-Infrared Surveyor (FIS), will provide the four-color all sky survey data in the 50-200 μm wavelength range with the diffraction-limited spatial resolution for the 67-cm diameter telescope. The world's first monolithic Ge:Ga 20x3 array directly attached to the cryogenic readout electronics (CRE) is used for the short-wave bands of the FIS of 50-110 μm. The stressed Ge:Ga array is built by stacking 15 pieces of the 5-element detector blocks, where each detector is installed in individual cavity, and it covers the long-wave bands of 110-200 μm. The cryogenic readout electronics for both short- and long-wave arrays consists of Capacitive Trans-Impedance Amplifier (CTIA) with p-MOSFETs array designed for low-temperature use. In this paper, we describe the current development status of these detectors, showing their structures and recent test results.

INTRODUCTION

Extrinsic photoconductors have long been used as the most sensitive detectors in the far-infrared range. Since the concentration of the doped impurity in the bulk-type photoconductor is limited up to 10^{16} cm^{-3}, the light absorption coefficient is generally low (~2 cm^{-1}), then the detector should be installed in the light cavity to keep a high efficiency. This is a major drawback of this type of detector in fabricating a large format array, which is essential to perform astronomical observations efficiently. The most popular photoconductor in the 100-200 μm range is stressed Ge:Ga. Requirement of the stressing mechanism is also disadvantage in constructing a compact detector, which is also important for space applications.

Contact information for S. Matsuura: Email: matsuura@ir.isas.ac.jp, phone (81) 42 759 8520

In order to overcome these drawbacks, we have developed a Ge:Ga array detector without the cavity and a compact stressed Ge:Ga array detector. These detectors were developed for the FIS (Far-Infrared Surveyor) instrument to be onboard ASTRO-F satellite[1, 2].

The ASTRO-F is the second Japanese infrared satellite, which is scheduled for launch in early 2004. The satellite will take the sun synchronous orbit and perform the all sky survey in the far-infrared bands in a half to one year. The telescope with the size of 67 cm in diameter, which is incorporated in the liquid-helium cryostat, is cooled to less than 6K. The FIS instrument including Ge:Ga photoconductor arrays is cooled down to about 2 K. Owing to high performance of the readout circuit and to high spatial resolution to minimize the source confusion, the point source detection limit of the FIS would be more than one order of magnitude better than that of the IRAS.

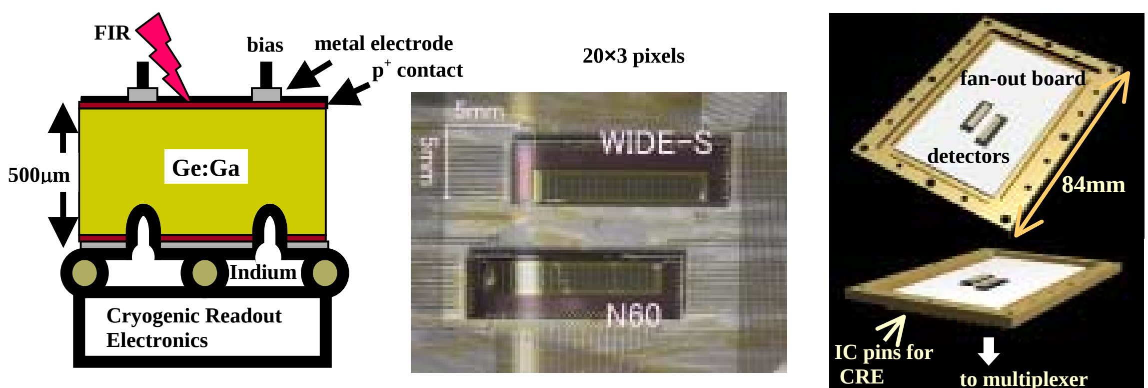
The FIS covers the wavelength range from 50-200 μm by two different detectors; short-wave (SW) and long-wave (LW) band detectors. The SW detector, which is responsible for the wavelength range from 50-110 μm, is the world's first two-dimensional monolithic Ge:Ga photoconductor array directly connected to silicon p-MOS cryogenic readout electronics (CRE). The longitudinal configuration for the SW detector is opening up the way of constructing much larger format array for future infrared missions. The LW detector for 110-200 μm is a compact stressed Ge:Ga photoconductor array with special cavity structure and stressing mechanism. Its size is several times smaller than the stressed Ge:Ga arrays for the other future infrared missions, e.g. SIRTF, Herschel. In this paper we describe design and performance of these detectors showing preliminary test results. Below we present the results for the SW detector. The results for the LW detector will be discussed in our future publications.

DESIGN OF THE FIS DETECTORS

Short-wave (SW) detector

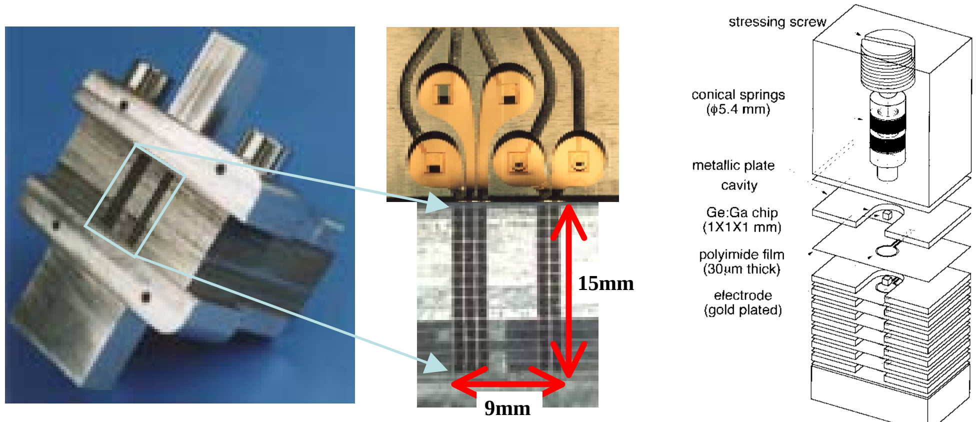
The SW detector is the first 2-D monolithic Ge:Ga photoconductor array which is directly attached to the CRE by the Indium bump technology. The device structure and the performance of the proto-type model are described in detail in previous papers[3, 4].

The structure of the detector are shown in Figure 1. The Ge:Ga photoconductor is produced by doping a 0.5-mm-thick Ge wafer with the Ga concentration of 1.6×10^{14} cm^{-3}. Small thickness of the detector has advantages of high photoconductive gain and of low radiation effect, though the quantum efficiency is sacrificed in the cavity-less configuration. The array structure is made by partitioning the Ge:Ga wafer into 20x3 of 0.5-mm-square pixels by the grid-shape transparent electrode. The ohmic contact is made by B+ ion implantation on the top and bottom surfaces to take the longitudinal configuration. All array pixels are electrically connected at the top contact, and the bias voltage is commonly applied to the whole array at the top contact. At the back contact the array pixels are electrically separated each other by 50-μm-wide, 30-μm-deep ditches. Each back contact is directly connected to the readout electronics with a 100-μm-diameter Indium ball, and the photocurrent is read out by the CTIA.



Co-produced by NEC, NEL, and Hamamatsu Photonics, assembled in CRL

Figure 1: *Structure of the SW detector array. Cross section (left) and top view (middle) of the array, and the array mounted on the fan-out board (right).*



Ge:Ga chips from CRL, assembled in Univ. of Tokyo

***Figure 2:** Structure of the LW detector array. Upper middle: the top view of a slice of the stack structure. 5 discrete detectors are installed in individual cavity. Right: stressing mechanism.*

As seen in Figure 1, the detector arrays for the narrow band (N60: 50-75 μm) and the wide band (WIDE-S: 50-110 μm) are identical, but for the N60 array only two detector columns are used. The band-pass filters are placed right in front of the arrays (not shown in the figure).
The arrays are attached to a fan-out board made of quartz substrate and then mounted on a rigid frame made of gold-coated KOVAR to minimize the thermal stress to the detector. The KOVAR frame is mounted on the aluminum housing with thermal isolation legs made of Vespel SP-1 and is thermally connected to the helium tank by a copper strap. The detector temperature is passively controlled to about 2.0-2.5 K by self-heat dissipation of the CRE (~1 mW) and the heater power. The total mass of the detector module is ~300g. The FM detector module has already passed the vibration test for simulating the mechanical stress at the launch.

Long-wave (LW) detector

The LW detector is the stressed Ge:Ga photoconductor array, of which the array format is 15x5 of 1-mm-square pixel. In order to minimize the whole detector volume, a stack array structure and a special stressing mechanism are adopted[5, 6]. As shown in Figure 2, the array structure is made by stacking 15 slices of 1-mm-thick cavity plate involving 5 discrete detectors in the individual cavities. The 15 detectors in the same array column are simultaneously stressed by a single conical spring. The ohmic contact are fabricated on the detector surfaces taking the transverse configuration, and the detectors in the same cavity plate are mounted with the readout electronics together on a flexible cable made of a polyimide film.
The detector module is mounted on an aluminum frame with a Vespel support and cooled down to 1.8 K via a heat strap directly connected to the helium tank. Total weight of the detector module is ~500g, which is much smaller than that of previous stressed Ge:Ga arrays with similar number of pixels.
In order to apply the stress onto all detectors uniformly, precise positioning of the detectors is essential. By positioning the detectors with the accuracy better than 10 μm, we have succeeded to apply the stress up to 400 N/mm^2 for the proto-type model. It is confirmed that the spectral response of this detector extends to ~200 μm and that the responsivity is sufficiently high, ~40 A/W at 30 mV bias. We have already assembled the FM detector module, measured its photo-response, and proved its thermal and mechanical strength via cooling and vibration tests. The FM array is presently in the final assembling process.

Cryogenic readout electronics (CRE)

The readout electronics for the FIS detectors is the capacitive trans-impedance amplifier (CTIA), which is located at the 2-K stage. The p-MOSFET for the CRE is specially designed for low temperature operation; the n+ layer is embedded in the substrate to keep the back-gate conductance even at the cryogenic temperature. The circuit works well at ~2 K without unstable behavior, such as kink effect and histerisis in the characteristic curve[7]. The OP-amp is designed to have the open-loop gain of ~1000, and the full range

of the output is to be ~0.5V for the feedback capacitance of 10 pF. The designed heat dissipation is ~0.2 μW/FET, which is low enough to keep the detector temperature to the best condition.
Each pixel in the array has individual CTIA, and the array columns are sequentially switched by 5-channel multiplexers. In the intermediate term in switching the column from one to another, the multiplexer selects the reference (GND) line in order to discharge the gate of the output source follower. The 20/15 (SW/LW) parallel signals from the multiplexers are handled by the A/D converters in the warm electronics.

DETECTOR PERFORMANCE

Responsivity

The responsivity was measured by using the blackbody source at the temperature of around 30 K, which is placed in the test dewer. In order to perform the measurement under low signal and background condition (~10^{5-6} photons/s) similar to that in the flight, a 0.1% ND filer is used. The infrared light to the detector is modulated by a cold shutter placed in front of the blackbody source.
Figure 3 is a typical CTIA output of the detector at the bias of 100mV for the source flux of approximately 10^6 photons/s. The integration time (reset time) of this data is 1s. Difference between the integration ramps for the source on/off states is clearly seen.
Shown in Figure 4 is the bias voltage dependence of the responsivity defined at the peak wavelength, around 100 μm. The responsivity measured at 80-mV bias, about a half of the break-down voltage, is 20 A/W, and it increases with increasing the bias quadratically, as is usually seen for single element devices.
The present detector is designed to have high quantum efficiency even without optical cavity. By using the multiple reflections between the both detector surfaces, the optical path length in the photoconductor can be much longer than the detector thickness. The quantum efficiency anticipated from the absorption coefficient and the detector thickness is 0.2. The measured responsivity the quantum efficiency at the peak wavelength corresponds to ~0.4, which exceeds the value expected from the absorption coefficient[3, 4]. The average responsivity in band is about a half of the peak value, but it is still much higher than that of the transverse-type devices. This high efficiency could be explained by the contribution of the B+ implanted layer to the photo-response[3].

Linearity

The responsivity is calculated from the average slope of the integration ramp shown in Figure 3, but the local slope shows scattering from the average value due to the noise and the nonlinearity. The local slopes calculated by the running differentiation between two data points separated by 0.1s are shown in Figure 5. The short-term fluctuation of the slope comes from the random noise, and the long-term variation is due to the nonlinearity of the integration ramp, which originates from the CRE.
Although the nonlinearity is about 20% for this data set and it may affect the calibration, this nonlinearity is systematic and correctable; it is fairly repeatable and depends almost only on the output dc-voltage. Since the linearity depends on the circuit parameter of the CRE, more accurate tuning would be helpful to obtain more linear ramp. The fine tuning of the CRE parameter for the FM array is going on as a main task.

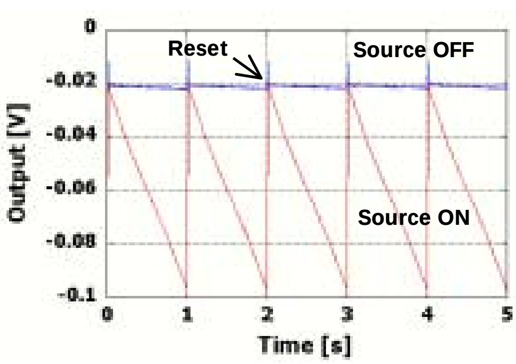


Figure 3: *Typical output signal.*

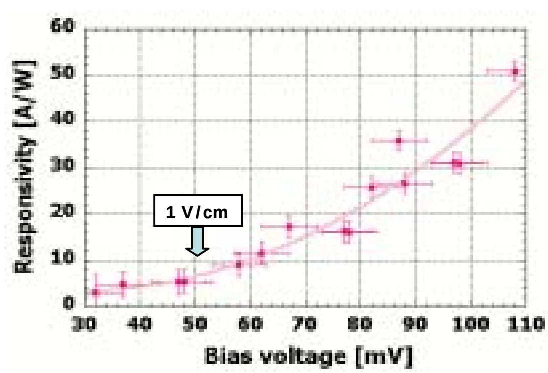


Figure 4: *Bias dependence of the responsivity.*

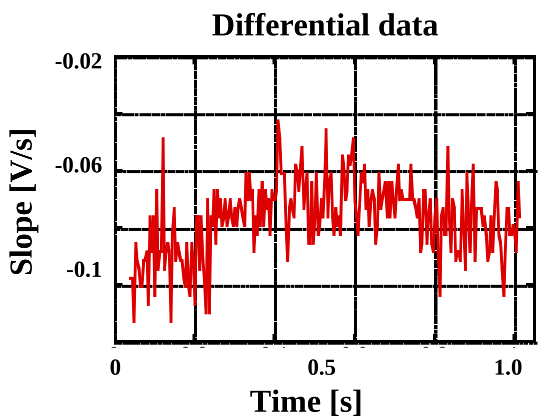


Figure 5: *The local slope of the integration ramp.*

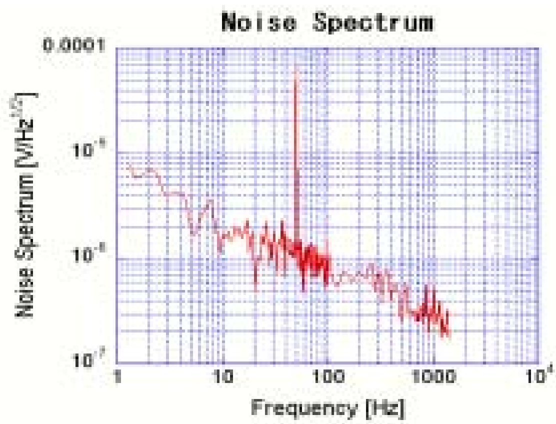


Figure 6: *Noise spectrum of the output..*

Noise

Shown in Figure 6 is the noise spectrum of the output under dark condition. The 1/f noise dominates in the spectrum, and it would originate from the CRE because of no dependence on the bias voltage. The overall noise obtained from the spectrum is 20μV. The noise equivalent power (NEP) for the integration time of 0.14s, which is the transit time of a point source across an array pixel in the all-sky survey, is estimated to be ~1×10^{-17} W, and the detection limit is ~70 mJy (5σ) for the WIDE-S band. For the LW detector, this noise figure gives the detection limit comparable to the confusion-noise-limited value of ~30 mJy.

Uniformity of responsivity

Uniformity of the responsivity in the array is practically important to perform the imaging photometry accurately, because highly non-uniform responsivity in the array causes large flat field error. The present device has some bad/dead pixels, and number of healthy pixels is ~70% of the total. The responsivity variation in the healthy pixels is approximately 20% of the average, 20 A/W at 80mV bias. This non-uniformity would be acceptably corrected by flat-fielding. Main cause of the non-uniformity is most likely the variation of the input offset voltage of the CRE, but the non-uniformity of the impurity concentration in the Ge wafer may contribute substantially.

Cross-talk

Because of its construction, monolithic arrays may show various kind of crosstalk between individual pixels. The cross-talk would affect not only the photometric accuracy but also the spatial resolution. We have measured the cross-talk by illuminating only a certain array pixel with a 0.4-mm pin-hole and measuring the signal at the other dark pixels. The observed cross-talk signal ranges from 10-20% of the signal at the illuminated pixel, depending on the bias voltage as shown in Figure 7. Although the diffraction should contribute to the cross-talk signal, it is estimated to be a few % and should not have bias dependence. Therefore, the bias dependent part of the cross-talk (~10%) is attributed to an electrical effect. The carrier diffusion from the main pixel to neighboring pixels due to carrier heating effect and/or inhomogeneous electric field in the device may be the cause of the electrical cross-talk.

Transient response

Slow transient response of the Ge:Ga photoconductor under low background condition has been reported by many authors. We also observed the slow response[8] to the step light input for the present device as shown in Figure 8. The time constant of the slow component is the order of 10s, and it depends on the bias voltage. In this measurement the background photon flux is ~1×10^{6} photons/s. The dependence of the transient behavior on the photon flux is also seen (not shown here) as is reported in previous works. In this measurement the hook anomaly is not clear or not strong, in accordance with a theoretical calculation for the longitudinal type device[9].

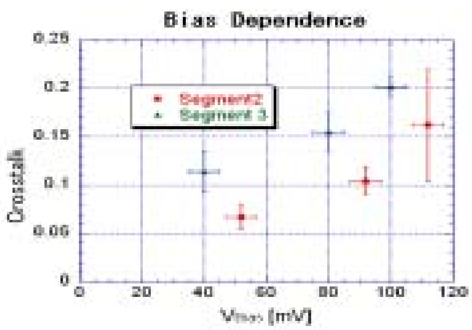


Figure 7: *Bias dependence of the cross-talk.*

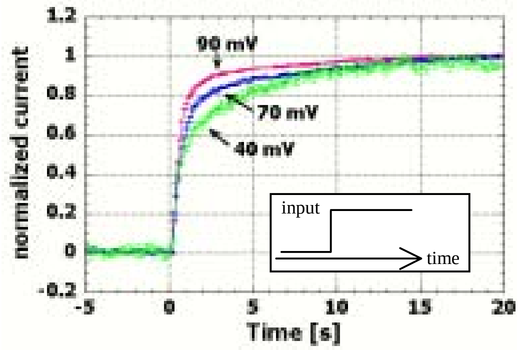


Figure 8: *Bias dependence of the transient response.*

We observed the transient response in the cross-talk signal as well, and its response is slightly slower than the main signal. Both physical and practical analysis for the transient behavior including the cross-talk, which would affect the photometric accuracy, is on-going work.

Radiation effect

The responsivity change by the cosmic ray hit is another important issue for the space-based instruments. We have investigated the responsivity change and its relaxation behavior including the effect of curing operation (bias boost, thermal annealing and IR illumination) under various photon flux and bias conditions, by irradiating the single element detectors (both Ge:Ga and stressed Ge:Ga) with gamma-ray sources[10], and most of the test results are half-quantitatively explained by theoretical models. For the FM detector, ~5 times increase of the responsivity was caused by the absorbed dose comparable to that of single passage across the SAA in the ASTRO-F orbit[8]. More measurements on the radiation effect for the FM detector and the flight simulation for the bias boost operation are planned in near future.

SUMMARY

We described the structure of the FIS detectors to be onboard the ASTRO-F and showed preliminary test results for the FM device. The test results show that the device works properly. The detailed performance evaluation as the FM detector is still underway. The basic concept for the present arrays, down-sizing with keeping high efficiency, is promising way to produce much larger format sensitive array for future infrared missions.

REFERENCES

1. H. Murakami: *Current Status of ASTRO-F,* ISAS Report SP No. 14, 267, 2000
2. M. Kawada: *FIS – Far-Infrared Surveyor onboard the ASTRO-F,* ISAS Report SP No. 14, 273, 2000
3. M. Fujiwara, et al.: *Development of far-infrared Ge:Ga photoconductor having a longitudinal configuration*, Appl. Phys. Lett. vol. 77, 3099, 2000
4. M. Fujiwara, et al.: *Development of far-infrared Ge:Ga photoconductor2D array for 3 THz imaging,* Proc. SPIE vol. 4130, 842, 2000
5. Y. Doi, et.al.: *Compact two-dimensional array of Stressed Ge:Ga detectors,* Experimental Astronomy, vol. 10, 393, 2000
6. S. Makiuti, et.al.: *Development of stressed Ge:Ga 2D array*, Proc. SPIE vol. 3354, 261, 1998
7. T. Watabe, et al.: *Evaluation of Cryogenic Readout Electronics for ASTRO-F,* this volume
8. H. Kaneda, et al.: *Evaluation of Transient Behavior of Ge:Ga detectors for ASTRO-F,* this volume
9. N.M. Haegel, et al.: *Origin of the hook effect in extrinsic photoconductors*, Appl. Optics vol. 40, 5748, 2001
10. H. Kaneda, et al.: *Laboratory Measurements of Transient Behavior of Stressed Ge:Ga Detectors,* 'The calibration legacy of the ISO Mission', proceedings of a conference, 2001, in press